Development of a GPS receiver for geosynchronous satellites toward autonomous operation

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Y. Nakajima [1], T. Yamamoto [1], T. Sekiguchi[1], K. Nishijo[2], R. Harada[3], M. Kasahara[3], S. Kawakami[3], and S. Kumagai[3]

[1] *Research and Development Directorate, Japan Aerospace Exploration Agency, 2-1-1 Sengen, Tsukuba, Ibaraki, 305-8505, Japan*
[2] *Space Technology Directorate I, Japan Aerospace Exploration Agency, 2-1-1 Sengen, Tsukuba, Ibaraki, 305-8505, Japan*
[3] *Space Engineering Division, NEC Space Technologies, Ltd., 1-10, Nisshincho, Fuchu, Tokyo, 183-8551, Japan*

Abstract

This paper presents the latest GPS receiver developed by JAXA and NEC Space Technologies, Ltd. for satellites in geosynchronous orbit. This marks the first attempt by a Japanese GPS receiver to use GPS signals above the GPS constellation of satellites. The expected signal strength is weaker at geosynchronous orbit than that observed at low Earth orbit. A new GPS receiver was developed to receive such signals and determine satellite position, by improving sensitivity and upgrading the software of the conventional GPS receiver used for LEO satellites. This paper introduces the newly developed GPS receiver for geosynchronous satellites and its performance as obtained by simulations and ground tests.

Keywords: GNSS, GPS receiver, geosynchronous satellite, onboard navigation, spaceborne

Introduction

Global Positioning System (GPS) is common method of observing the position and velocity of low Earth orbit (LEO) satellites. By using the GPS receiver, it is possible to determine a satellite's position onboard with high precision, thereby enabling the satellite operators to maintain the satellite's orbit autonomously.

However, it is difficult to use GPS signals at such high-altitude orbits as Geosynchronous Earth Orbit (GEO), and thus the GPS has only recently been put to practical use. As the GPS was primarily developed for ground users, its signal is transmitted toward the surface of Earth. Most of the signals radiated from the GPS satellites are received on Earth, but weak signals emitted from the edge of the antenna's main lobe or sidelobe can be received by a satellite at GEO as illustrated in Fig. 1. The signal observable at GEO is about 20 dB weaker than that observed at LEO due to longer distance from the transmitter to the receiver, and consequently cannot be handled by the receiver for LEO.

Given the original intention not to use the sidelobe of the conventional GPS satellite, the sidelobe pattern was not specified. But experimentally loaded GPS receiver (GPSR) on Galileo In-Orbit Validation Element (GIOVE) [1] flying 3000 km higher than GPS constellation revealed that the GPS broadcast stronger signal than expected, therefore the GPSR could possibly be used at GEO by improving the sensitivity of a general spaceborne GPSR. Actually, the US early warning satellite (SBIRS GEO-1) launched in 2011 installed a GPSR, and pseudo range was obtained to evaluate its accuracy [2]. Navigator GPSR installed on Magnetic Multiscale (MMS) mission marked the first attempt to use GPS for onboard navigation above GPS constellation [3]. Geostationary Operational Environmental Satellite-R also installed a GPSR to obtain onboard navigation at GEO [4].

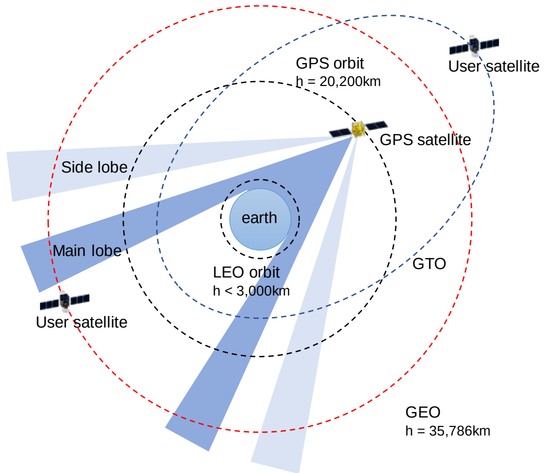

Fig. 1: Geometric configuration of receiving GPS signals at GEO

Conventionally, range and range rate (R&RR) using radio wave observation from the ground has been used as a means of determining the orbits of geostationary satellites. This method accumulates the round-trip time of radio waves from one or more ground stations for several to several tens of hours to determine the orbit within an accuracy of a few kilometers [5]. Determining satellite position by R&RR requires precise ground station equipment and entails the ground stations being occupied for long periods of time, making the presence of operators handling those systems indispensable. And because GEO is a high-demand orbit, controlling several satellites in a single control slot would also be desirable, although difficult to realize with current navigation accuracy. Moreover, it is important to note that propulsion systems cannot generally be used during the orbit determination process by R&RR because such use adversely affects orbit determination accuracy.

By using the GPSR the navigation solution is derived in real-time, then R&RR operation at the ground can be simplified. Moreover, if the orbit can be determined by GPSR with higher accuracy than that of R&RR, two or more satellites can be controlled in a single GEO control slot, so called “collocation”, so as to fully exploit the precious GEO.

In order to use GPS at GEO, JAXA and NEC Space Technologies, Ltd. jointly developed a new GPSR for GEO satellites. This receiver is based on the GPSR for LEO developed in 2013 [5,6], and its hardware applied common design as much as possible while increasing its sensitivity by upgrading the software and antenna. The GEO GPSR is scheduled to be launched with Engineering Test Satellite 9 (ETS-9), which is a geostationary satellite currently under development at JAXA. Prior to ETS-9, the optical data relay satellite (JDRS) plans to acquire data by using a partially modified GPSR, which is basically a GPSR for LEO with its software and antenna modified for GEO satellites.

ETS-9 is an all-electric satellite with no chemical propulsion system, relies on electric propulsion to conduct all orbit controls. Compared to chemical propulsion, electric propulsion has small thrust, resulting in a longer thruster firing time than that of satellites using chemical propulsion, as well as the need for frequent application. In conventional R&RR, trajectory control where acceleration is generated cannot be performed during observation, which imposes a large restriction on operation. However, by using the GEO GPSR, it is possible to constantly obtain the navigation results even during orbital control, thereby enabling autonomous orbit determination and trajectory control.

GPS Receiver Design

The GEO GPSR is currently under development based on the Japanese 5th generation GPSR developed for LEO satellites in 2013 [6]. The GEO GPSR shared hardware design with GPSR for LEO as much as possible to reduce development cost.

Table 1: Specifications of GPSR

Contents	Specification
Dimensions (nom)	96 mm×225 mm×158 mm
Mass (nom)	3.0 kg
Power Consumption	< 22.0 W
Channels	12 C/A code
Acquisition C/N0	20 dB-Hz
Tracking C/N0	17 dB-Hz

*Table 2: Navigation Accuracy *[1-10]*

Item		Measurement update mode	Propagation mode
Position	Along	6 [m]	70 [m]
	Cross	4 [m]	70 [m]
	Radial	30 [m]	80 [m]
Velocity	RSS	0.03 [m/s]	0.22 [m/s]
Pulse timing accuracy		±160 [ns]	±1.7 [μs]

*1: Measurement update mode is applicable 600 s after filter converges.
*2: Propagation mode is valid for 600 s after filter measurement stops.
*3: Navigation performance satisfies its specification 95% of the time within 24 hours.
*4: Ionospheric delay is assumed to be the level of 1957, the maximum period.
*5: Multipath and GPS transmitter antenna group delay are not considered.
*6: The antenna transmitter pattern of all GPS satellites is assumed to be Block IIR-M.
*7: More than 24 GPS satellites are assumed to be available without SA.
*8: SIS-URE is assumed to be 1.0 m (RMS).
*9: If acceleration over 0.3 mm/s^2 is applied, the navigation specifications are not approved three hours after thruster ON or OFF.
* 10: GEO GPSA is assumed to be pointing toward Earth within 1°.

Receiver Design

As the number of tracked satellites was expected to be reduced at GEO, the filter time constant was set longer than that of the conventional GPSR. For that reason, a clock (OCXO) with long-term stability and a small jump in frequency was adopted.
In order to improve sensitivity, the GPSP correlators have been modified to detect correlation by prolonging the power integration time from those for LEO. Moreover, false tracking was reduced by adding false tracking detection algorithm. Due to these modifications, the search time per satellite has been increased, thereby raising the possibility of acquisition not being completed during the visible time and navigation not being started. Therefore, the GEO GPSR reduces the search time per satellite by performing parallel processing on the correlator's 36 channels. Table 1 lists the specifications of the GPSP, and Table 2 summarizes the navigation accuracy. Two kinds of navigation accuracy are defined according to the state of the filter: Kalman Filter (KF) with measurement update and without measurement update (propagation mode). The navigation solution is nominally derived through KF with measurement update. Even if a fewer satellites are tracked by accident, this GPSR propagate the state to obtain the position and velocity of the satellite within the accuracy shown in Table 2 for 600 s. In usual, the number of the tracked GPS satellite will be gained, and the measurement update will be restarted within 600 s.
In addition, the housing of the GPSR was made thicker than that of the LEO GPSR by 1 mm and the material was changed to improve total dose tolerance. The GPSR was designed to endure 1 year at GTO and 15 years at GEO. Basically, all the materials were chosen to have enough tolerance against single event latch-up and upset, and for those the tolerance cannot be guaranteed, the possibility of single event was analysed and confirmed to be low enough. Even if the single events occur, the single event detection and recovery algorithm will be performed and recover from the single events.

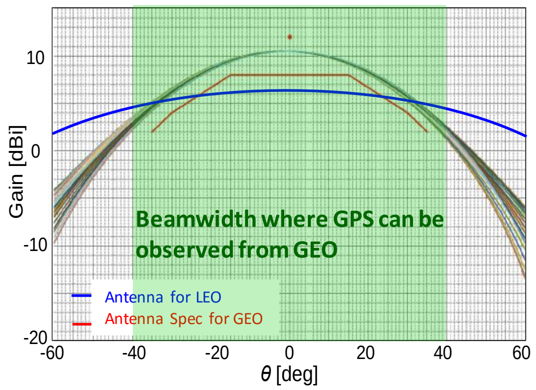

Fig. 2: GEO GPSA antenna pattern

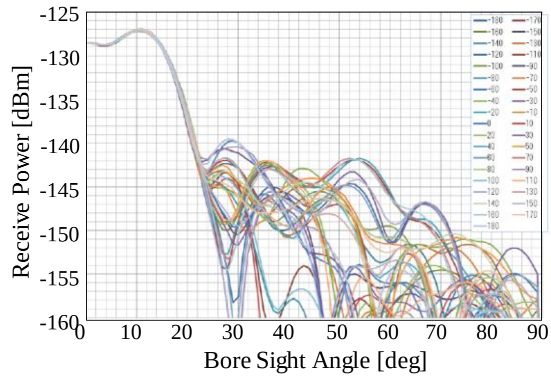

Fig. 3: Modeled transmitter antenna pattern

Antenna Design

GPS satellites are observed from GEO satellites in a particular direction around the Earth as shown in Fig. 1. From GEO, most of the GPS satellites can be observed within 35° from nadir direction. To take advantage of this characteristic, the GEO antenna was designed to make its antenna pattern narrow and its peak gain high to improve the chance to receive signals. As it is necessary to install the GPSA on the satellite's mission plane facing the Earth where much of the mission equipment is installed, the GPSA size and height must be designed as small as possible while achieving high peak gain. Therefore, we adopted the patched array and designed a thin, small antenna for the GEO GPSR. The developed narrow beamwidth antenna pattern is shown in Fig. 2. The GPS satellite for LEO was designed with a beamwidth of ± 80° because GPS satellites are observed in a wide range, while the GPSA for GEO narrowed its beamwidth down to 35°. Narrowing the beamwidth resulted in exceeding peak gain by 10 dBi which is 5dB stronger than LEO GPSA. We have verified through testing that the developed antenna had the designed antenna pattern, and that gain higher than the required specification.

Simulation Results

This section explains the navigation simulation results of the GEO GPSR. The number of GPS satellites, GPS initial position, and thruster control profile of the user satellite were varied in a total of 1728 cases to verify the performance in wide range of situations. The detailed conditions are listed in Table 3. Acceleration of the thruster control was set to be 0.3 mm/s^2, which assumed general electrical propulsion. The antenna pattern of the published GPS Block IIR-M [7] shown in Fig. 3 was applied to all satellites. 40% of GPS satellites are Block IIF, which has different antenna pattern, however their difference was quite small for first and second lobe of the antenna [1]. According to GPS ICD document IS-GPS-200H [8], the offset power was set so that the minimum received power on the ground became -158.5 dBW.

Simulation parameters are listed in Table 4. Multipath and transmitter antenna group delay were set to zero and the GPS broadcasting error was set to 1.0 m (RMS). The observation error was modelled by a function of C/N0 by fitting the experimentally obtained data. Ionospheric and tropospheric delay was calculated in the simulation, however the onboard navigation software eliminates those signals from low elevation angle, probably passed through the ionosphere and troposphere. The perturbations of gravity by the Earth, the Sun, and the Moon were modelled in the simulation, as was solar radiation pressure. The sun and the moon gravity model in the filter were intentionally changed to imitate the modelling error.

Fig. 4 shows example cases of the simulations by measurement update mode and propagation mode. The results revealed that navigation performance achieves the design goal of this GPSR for 95% of the simulated time (48 hours). The weak acceleration generated by electrical propulsion can be estimated as empirical acceleration and compensated. The worst value in the 1728 cases are listed in Table 5. We thus confirmed that the development specifications have been achieved regardless of orbital control profile.

Table 3: Simulated conditions

Item	Content
Orbit	GEO
Attitude	Earth pointing
Orbit control	1. no thruster firing 2. 0.3mm/s^2 in-plane & out-plane control
Duration	48 hours
GPS number	24, 27, 30
GPS initial position	Ascending node; 24 cases True anomaly; 12 cases
GPS antenna model	Setting GPS Block IIR-M data for all the GPS
GPSA orientation	Nadir direction

Table 4: Model of the simulation

Item	Simulator model	Filter
Multipath	None modeled	N/A
Antenna group delay	0.0 m	N/A
Ionospheric delay	The maximum delay observed in 1957	Signals from nadir direction are eliminated
SIS-URE	1.0 m (RMS)	N/A
Observation error	Function of C/N0 from the experimental result	N/A
Perturbation	Earth gravity; 50th order EGM96 Sun & Moon gravity; Modelled with 5% error Solar radiation; Modelled	Earth gravity; 20th order EGM96 Sun & Moon gravity; Modelled Solar radiation; None modelled

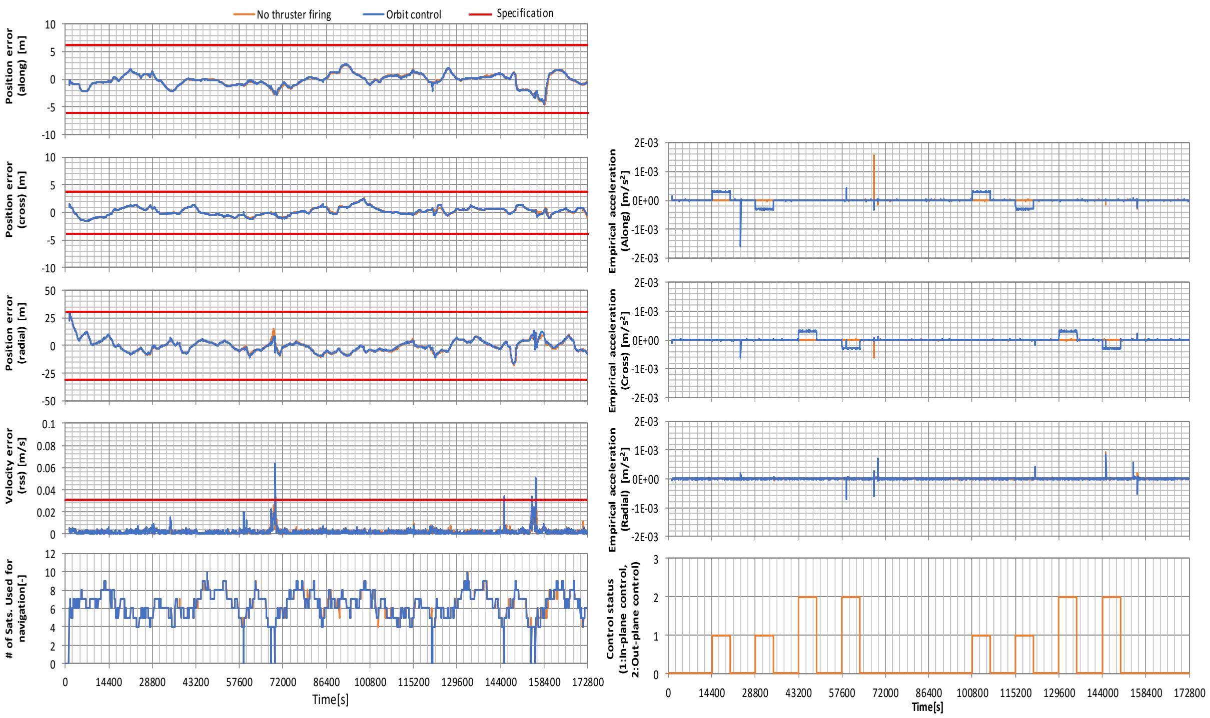

Fig. 4: Simulation results of GPSR navigation

Table 5 Navigation accuracy results

Condition	GPS number	Position error (95%) [m]			Velocity error RSS (95%) [m/s]	Average GDOP	Number of used sat.
		Along	Cross	Radial			
Specification	N/A	6	4	30	0.03	N/A	N/A
Orbit control	24	4.8	2.7	21.6	0.006	34.1	6.1
	27	4.5	2.5	20.7	0.007	33.9	6.7
	30	4.4	2.4	16.8	0.005	29.8	7.4
No thruster firing	24	4.9	2.8	21.4	0.006	34.3	6.1
	27	4.4	2.6	20.7	0.008	34.0	6.7
	30	4.2	2.4	16.5	0.005	29.8	7.4

Conclusion

JAXA and NEC Space Technologies, Ltd. have developed a new GPS receiver for geostationary satellites. Given the weak GPS signal observed in GEO, we intended to improve receiver sensitivity and stabilize the navigation filter. We also developed a new antenna for the GEO GPSR with a narrow beamwidth antenna sensitive only to the necessary direction. We conducted a series of simulations to validate acquisition, tracking, and navigation at GEO. The number of GPS satellites, their initial position, and the trajectory control profile of the user satellite were varied in total of 1728 cases to evaluate its performance under wide variation of the situations. The simulation results showed that the newly developed GPSR satisfied its specifications, which are suitable for satellites with a low power thruster system such as electrical propulsion. The real-time determination of position by the GPSR promotes the automation of orbit control at GEO. And thanks to navigation accuracy higher than that of conventional orbital determination by R&RR, highly accurate position control is possible, which would enable the effective use of precious GEO, such as controlling multiple satellites in a single control slot.

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